MICROBOLOMETER FOCAL PLANE ARRAY METHODS AND CIRCUITRY

Dr. William J. Parrish

Jeffrey L. Heath

5   Naseem Y. Aziz

Joseph Kostrzewa

George H. Poe

BACKGROUND OF THE INVENTION

10 Field of the Invention

The present invention relates generally to focal plane arrays and, more particularly, to microbolometer focal plane arrays.

Related Art

15   A microbolometer, which detects infrared radiation, is well known in the art. Modern microbolometer structures are typically fabricated on monolithic silicon substrates to form an array of microbolometers, with each microbolometer functioning as a pixel to produce a two-dimensional image. The change in

20   resistance of each microbolometer is translated into a time-multiplexed electrical signal by circuitry known as the read out integrated circuit (ROIC). The combination of the ROIC and the microbolometer array is commonly known as a microbolometer focal plane array (FPA) or microbolometer infrared FPA.

25   Microbolometers are described in further detail in U.S. Patent Nos. 5,756,999 and 6,028,309, which are herein incorporated by reference in their entirety.

Microbolometer array performance is typically degraded due to non-uniform responses among the individual microbolometer

- 1 -

detectors to uniform incident infrared radiation. Factors
contributing to the performance degradation include variations
in the infrared radiation absorption coefficient, resistance,
temperature coefficient of resistance (TCR), heat capacity, and

5   thermal conductivity of the individual detectors. Because the
magnitude of the non-uniformity can be substantially larger than
the magnitude of the actual response due to the incident
infrared radiation, various techniques are typically required to
compensate for the non-uniformity and acquire the portion of the

10   signal representing the incident infrared radiation.

Fig. 1 illustrates a conventional method for measuring the
microbolometer resistance. A voltage (V) is applied across the
series combination of a microbolometer 3 (that can receive
incident infrared radiation 1) and a resistive load (R_{load}) 6. An

15   output voltage (Vout) is measured across microbolometer 3 to
determine its resistance ($R_{bolometer}$), according to the following
equation.

$$R_{bolometer} = R_{load}/(V/V_{out} - 1)$$

The temperature rise in microbolometer 3 due to self-

20   heating generally is significantly larger than the temperature
rise resulting from the incident infrared radiation. If the
voltage (V) is multiplexed or periodically applied during each
sample period, the self-heating behavior is as shown in Fig. 2.
The microbolometer temperature rises significantly during each

25   sample period (also referred to as a bias period and indicated
by a pulse bias spike in the figure).

One drawback of this characteristic is that the pulse bias
heating causes the microbolometer 3 (also referred to as the
active microbolometer and which is thermally isolated from the

30   substrate) to operate at a different temperature than resistive

- 2 -

load 6 (which may also be a microbolometer and referred to as
the load microbolometer that is thermally shorted to the
substrate). Also, various other non-uniformities or variables
between microbolometer 3 and resistive load 6 may cause a

5   difference in the TCR between the two microbolometers. Thus,
the pulse bias heating and other factors contribute to a
mismatch in relative TCR between resistive load 6 and
microbolometer 3.

This mismatch in relative TCR limits the range of operating

10   temperatures for the microbolometer array. For example, as
shown by the graph in Fig. 3, the output voltage for a
microbolometer in the microbolometer array drops below the
minimum dynamic range of the system prior to reaching the
maximum desired substrate temperature. Alternatively as shown

15   in Fig. 4, the output voltage for another microbolometer in the
microbolometer array rises above the maximum dynamic range of
the system prior to reaching the maximum desired substrate
temperature.

For a typical microbolometer array, the output voltage

20   produced by each microbolometer may vary over substrate
temperature significantly, as shown in Fig. 5, for six exemplary
microbolometers from the microbolometer array. The average
output voltage from a certain number of microbolometer elements
exceeds the minimum and maximum signal range, as shown in the

25   histogram in Fig. 6, resulting in unsatisfactory FPA performance
within the desired temperature range of operation.

Conventional microbolometer arrays often provide a
correctable output only within a small range of substrate
temperatures, on the order of 0.005 to 0.025 degrees Kelvin. A

30   thermo-electric cooler, temperature sensor, and temperature
control electronics are employed to maintain the substrate

temperature within this range to minimize microbolometer array

non-uniformities, which adds to system cost and complexity. As

a result, there is a need for techniques that address

microbolometer array properties and non-uniformities over a

5   wider range of temperatures.

BRIEF SUMMARY OF THE INVENTION

        Microbolometer circuitry and methods are disclosed herein.

In accordance with one embodiment, microbolometer focal plane

10   array (FPA) circuitry is disclosed that provides temperature

compensation over a wide temperature range. The relative

mismatch in TCR between the active microbolometers and the load

or reference microbolometers is compensated to allow the removal

of strict temperature stability requirements. For example,

15   rather than requiring temperature stability of the

microbolometer array to within a fraction of a degree, the

operating temperature range may be expanded significantly, such

as from -40° to 55°C. Methods are also disclosed for providing

calibration and applying the calibration values to the

20   microbolometer FPA circuitry and to processing of the resulting

signal values from the microbolometer FPA circuitry. Thus,

circuitry and methods disclosed herein overcome many of the

disadvantages of the prior art, such as complex and costly

cooling systems, and provide infrared technology more applicable

25   to low-cost, high-volume commercial markets.

        More specifically, in accordance with one embodiment of the

present invention, a microbolometer circuit includes a first

microbolometer, a variable resistor coupled to the first

microbolometer, and a biasing circuit coupled to the first

microbolometer or the variable resistor to provide a load current.

In accordance with another embodiment of the present invention, a method of calibrating a microbolometer detector circuit includes calibrating a variable resistor to compensate for a relative temperature coefficient of resistance between an active microbolometer and a load over a desired temperature range; and calibrating an offset for an output signal generated by the microbolometer detector circuit.

The scope of the invention is defined by the claims, which are incorporated into this section by reference. A more complete understanding of embodiments of the present invention will be afforded to those skilled in the art, as well as a realization of additional advantages thereof, by a consideration of the following detailed description of one or more embodiments. Reference will be made to the appended sheets of drawings that will first be described briefly.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a conventional circuit for measuring microbolometer resistance.

Fig. 2 shows a graph of microbolometer temperature over many sample periods.

Fig. 3 shows a graph of microbolometer circuit output voltage as a function of substrate temperature.

Fig. 4 shows a graph of another microbolometer circuit output voltage as a function of substrate temperature.

Fig. 5 shows a graph of six microbolometer circuit output voltages from a microbolometer array as a function of substrate temperature.

Fig. 6 shows a histogram of microbolometer circuit output

5   voltage for a microbolometer array relative to a desired signal range.

Fig. 7a shows a circuit for providing temperature compensation in accordance with an embodiment of the present invention.

10   Fig. 7b shows a circuit for providing temperature compensation in accordance with another embodiment of the present invention.

Fig. 8 shows a graph of microbolometer circuit output voltage as a function of substrate temperature in accordance

15   with an embodiment of the present invention.

Fig. 9 shows a graph of microbolometer circuit output voltage as a function of substrate temperature, which illustrates temperature compensation techniques, in accordance with an embodiment of the present invention.

20   Fig. 10 shows a graph of microbolometer circuit output voltages from a microbolometer array after implementation of temperature compensation techniques in accordance with an embodiment of the present invention.

Fig. 11 shows a histogram of microbolometer circuit output

25   voltage for a microbolometer array relative to a desired signal range after implementation of temperature compensation techniques in accordance with an embodiment of the present invention.

Fig. 12 shows a circuit providing temperature compensation in accordance with another embodiment of the present invention.

Fig. 13 shows exemplary circuitry for a circuit element in accordance with an embodiment of the present invention.

5   Fig. 14 shows exemplary packaging for a microbolometer FPA in accordance with an embodiment of the present invention.

Fig. 15 is a top-level flowchart of a calibration process in accordance with an embodiment of the present invention.

Fig. 16 is a detailed flowchart for a step of the flowchart
10   in Fig. 15.

Fig. 17 is a detailed flowchart for a step of the flowchart in Fig. 15.

Fig. 18 is a detailed flowchart for a step of the flowchart in Fig. 15.

15   Fig. 19 is a detailed flowchart for a step of the flowchart in Fig. 15.

Fig. 20 shows a graph and accompanying table illustrating a calibration operation in accordance with an embodiment of the present invention.

20   Fig. 21 shows a graph and accompanying table illustrating a calibration operation in accordance with an embodiment of the present invention.

Fig. 22 shows a graph and accompanying table illustrating a calibration operation in accordance with an embodiment of the
25   present invention.

Fig. 23 illustrates a compensation process in accordance with an embodiment of the present invention.

Fig. 24 shows a circuit for providing temperature compensation in accordance with another embodiment of the present invention.

Fig. 25 shows a circuit for providing temperature compensation in accordance with another embodiment of the present invention.

Fig. 26 shows a circuit for providing temperature compensation in accordance with another embodiment of the present invention.

Fig. 27 shows a microbolometer read-out integrated circuit with bias-correction circuitry and interface system electronics in accordance with an embodiment of the present invention.

The preferred embodiments of the present invention and their advantages are best understood by referring to the detailed description that follows. It should be appreciated that like reference numerals are used to identify like elements illustrated in one or more of the figures.

DETAILED DESCRIPTION OF THE INVENTION

Fig. 7a shows a circuit 20 providing temperature compensation in accordance with an embodiment of the present invention. Circuit 20 includes supply voltages 22 and 40, microbolometers 24 and 36, resistors 26 and 38, transistor 30, amplifier 32, and a digital-to-analog converter (DAC) 34. As explained in detail herein, circuit 20 provides substrate

temperature compensation and TCR mismatch compensation for the active and load microbolometers.

The active microbolometer is the thermally isolated microbolometer 24 that receives incident infrared radiation 1.

5   Microbolometer 24 is biased by supply voltage 22 and a load current (Ibias). Amplifier 32 provides the gate bias for transistor 30 (an NMOS transistor), while DAC 34 is used to set a reference voltage and control amplifier 32 to set the appropriate gate bias for transistor 30. Alternatively,

10   amplifier 32 can be eliminated and DAC 34 used to set the appropriate gate bias directly for transistor 30. A load circuit or bias circuit includes supply voltage 40, resistor 38, microbolometer 36, transistor 30, and amplifier 32 with DAC 34, which are used to establish the load current (Ibias).

15   Microbolometer 36, which is a thermally shorted (to the substrate) load microbolometer, is used as a substrate temperature compensated load. Supply voltage 40 is set to optimize the operating point for circuit 20 by setting the nominal voltage drop across microbolometer 36. An output

20   voltage (Vout) 42 of circuit 20 is provided at a node 41.

Fig. 7b shows a circuit 44 for providing temperature compensation in accordance with another embodiment of the present invention. Circuit 44 is similar to circuit 20, but includes an amplifier 28, which amplifies the voltage at node 41

25   to provide an output voltage (Vout) 46. Amplifier 28 is an exemplary circuit element to provide amplification or buffering for the voltage at node 41, if desired. As with amplifier 32, a DAC may provide the reference voltage (Vref) for the amplifier or the reference voltage may be at a set voltage level (e.g.,

30   ground). It should be apparent that output voltage (Vout) 42 may be translated, amplified, or converted by amplification or

- 9 -

integration processes and/or other well known signal processing techniques. Further references herein to output voltage (Vout) 42 would be also applicable to output voltage (Vout) 46.

In terms of general circuit operation for circuits 20 and 44, as incident infrared radiation 1 levels increase, the temperature of microbolometer 24 increases, which lowers its resistance, reduces the voltage drop across microbolometer 24, and increases the voltage level at the drain terminal of transistor 30 (i.e., node 41). This change in the voltage drop across microbolometer 24 causes a change in output voltage (Vout) 42. Therefore, as incident infrared radiation 1 levels increase or decrease, this is reflected by the voltage level of output voltage (Vout) 42 increasing or decreasing, respectively.

In general, supply voltage 40 is used to adjust the load current and thereby optimize the operating point of the circuit by setting output voltage 42 at a desired point within a range of output circuitry voltage levels. Specifically, by setting the appropriate gate bias of transistor 30 and appropriate voltage level of supply voltage 40, the output voltage (Vout) 42 is adjusted.

For example, supply voltage 40 may be a single voltage level set for the entire array of microbolometers. Amplifier 32 and DAC 34 are then used to supply a unique voltage bias to each corresponding thermally-shorted microbolometer 36 in the FPA to provide a fine adjustment or offset to the load voltage or the load current (Ibias). This corrects for the individual offset errors in the output signals from each of the thermally-isolated microbolometers (e.g., microbolometer 24). By adjusting the offset for each microbolometer circuit, the nominal output voltage level of output voltage (Vout) 42 for each circuit is adjusted to fall within a desired range.

To address the relative mismatch in TCR between microbolometer 24 (the active microbolometer) and microbolometer 36 (the load microbolometer), resistors 26 and 38 are provided. Resistor 26 is a variable resistor to generally provide fine

5   adjustments to the composite TCR value of the active microbolometer portion of the circuit relative to the load microbolometer portion of the circuit. Thus, for the voltage divider network of resistors, resistor 26 adjusts the composite TCR of microbolometer 24 and resistor 26 relative to

10   microbolometer 36 and resistor 38. As an example, circuit values for these circuit elements are 100 KΩ and 300 KΩ for microbolometers 24 and 36, respectively, but these values are not limiting and may vary over a large range, such as for example 50-200 KΩ and 150-600 KΩ, respectively. Exemplary

15   circuit values for resistors 26 and 38 may, for example, vary within 0-10 KΩ and 0-30 KΩ, respectively, but this range is not limiting and may vary over a wider range of values.

Resistors 26 and resistors 38 are typically resistors having a different TCR (generally lower) than respective

20   microbolometers 24 and 36. For example, resistor 26 may have a low TCR and microbolometer 24 may have a higher TCR relative to microbolometer 36. Consequently, by the proper selection of resistance value for resistor 26, the combination of resistor 26 and microbolometer 24 provides a TCR that is much closer to the

25   TCR of microbolometer 36 than is the TCR of solely microbolometer 24. Therefore, the performance and behavior of each microbolometer within the array is vastly improved over a range of substrate temperatures.

The following equation illustrates the combined or

30   composite TCR for a microbolometer in series with a variable

- 11 -

resistor (i.e., microbolometer 24 and resistor 26) as a function of temperature.

$$TCR = (\ TCR_{Bo}\ R_B(T)\ /\ (R_B(T)\ +\ R_{Trim}))$$

TCR, TCR_{Bo}, $R_B(T)$, and R_{Trim} represent the effective combined TCR

5   (labeled TCR), the TCR of the microbolometer (labeled TCR_{Bo}), the resistance of the microbolometer at a given temperature (labeled $R_B(T)$), and the resistance value of the variable resistor (e.g., to a first order constant as a function of temperature and labeled R_{Trim}), respectively. This equation illustrates how the

10   combined TCR is adjusted depending upon the resistance value of the variable resistor.

Resistor 38 provides the coarse adjustment for circuit 20. Consequently by setting resistor 26, temperature compensation is provided for the mismatch in relative TCR between the active

15   microbolometer and the load microbolometer. A calibration procedure as a function of the substrate temperature is performed to determine the appropriate value for resistors 26 and 38. Details of an exemplary calibration procedure are provided below.

20   The relative mismatch in TCR is driven by various factors, such as pulse bias heating, non-uniformities among microbolometers, and relative contact resistance between the active microbolometer and the load microbolometer and the substrate. The characteristics discussed above for Figs. 3

25   through 6 are attributable to a certain extent to the relative mismatch in TCR between the load and active microbolometer. Ideally, by accounting for the relative mismatch in TCR and offset as a function of substrate temperature, the output voltage for a given microbolometer circuit will be well behaved

30   as shown in Fig. 8. As can be seen, for a certain level of

received incident infrared radiation, the microbolometer circuit output voltage falls within a small percentage (e.g., twenty percent) of the minimum and maximum dynamic range over the desired substrate temperature range (e.g., 100°C).

5   Fig. 9 shows a graph of microbolometer circuit output voltage as a function of substrate temperature, which illustrates temperature compensation techniques, in accordance with an embodiment of the present invention. Curves 51 through 54 in the figure illustrate, for a given offset, the output

10   voltage for a microbolometer for various resistor trim values (e.g., output voltage 42 for various values of resistor 26).

          For example, in reference to Fig. 7a, if the relative mismatch in TCR between microbolometer 24 and microbolometer 36 is such that as the substrate temperature rises, the resistance

15   of microbolometer 24 decreases at a faster rate than microbolometer 36, output voltage 42 will increase as the substrate temperature rises for a given level of incident infrared radiation. This may be represented by curve 51 (Fig. 9) for a minimum resistor value for resistor 26.

20   If the measurements were repeated over the same substrate temperature range but the resistor value for resistor 26 was increased and the offset adjusted so that output value 42 is returned to the initial value for minimum substrate temperature (as shown in Fig. 9), output voltage 42 will increase at a lower

25   rate. This may be represented by curve 52. This process could be repeated for various values of resistor 26 to obtain curves, such as curves 53 and 54. It should be clear that from among curves 51 through 54, curve 54 provides the best response over the desired substrate temperature. Furthermore, this procedure

30   could be performed to obtain optimal resistor settings for each

- 13 -

microbolometer in the array to achieve performance such as illustrated in Figs. 10 and 11. Note that a detailed exemplary calibration process and operational application are discussed in detail below.

5   Fig. 10 shows a graph of microbolometer circuit output voltages from a microbolometer array after implementation of temperature compensation techniques discussed herein. After calibration of a number of microbolometers in the array to compensate for offset and relative mismatch in TCR, all of the
10   microbolometer circuit output voltages fall within a small percentage of dynamic signal range across the desired substrate temperature range. Furthermore, as shown in the histogram in Fig. 11, all of the microbolometer circuit output voltages within the array fall within the available signal range and
15   provide a predictable response. The microbolometer FPA performance illustrated in Figs. 10 and 11 represents a significant improvement over conventional microbolometer FPA performance, such as illustrated respectively in Figs. 5 and 6.

        As another example, resistor 26 and microbolometer 24 may
20   have a lower composite TCR relative to microbolometer 36, with resistor 26 having a lower TCR than microbolometer 24. Output voltage (Vout) 42 would have a response, for example, such as shown in Fig. 3. Thus, the contribution of any resistance by resistor 26 would only further degrade performance due to its
25   low relative TCR. However, by the proper selection of a resistance value for resistor 38, which has a lower TCR than microbolometer 36 (the load), the composite TCR of resistor 38 and microbolometer 36 is lower than the TCR of microbolometer 24, producing a curve, for example, as shown in Fig. 4. Thus,
30   resistor 26 can then be set, as discussed above, to obtain the desired output response, such as illustrated in Fig. 8.

It should be understood that Figs. 7a and 7b is an exemplary circuit to illustrate the relative TCR mismatch and temperature compensation techniques and that numerous modifications and variations are possible in accordance with the

5 principles of the present invention. For example, resistor 38 may not be necessary, depending upon the characteristics of the microbolometers within the array. Resistors 26 and 38 may be implemented as parallel resistance, rather than series, relative to respective microbolometers, or some combination of series and

10 parallel resistance may be implemented. The circuit arrangement may also vary, such as by interchanging the positions of resistor 26 and resistor 38 or the positions of microbolometer 24 and microbolometer 36. Additionally, one or more techniques discussed or referenced herein may be combined or selectively

15 implemented, depending upon the application or various other factors.

Circuit 20 in Fig. 7a (or circuit 44 in Fig. 7b) can be implemented in an array configuration, with a portion of circuit 20 placed in the unit cell while the remainder is placed outside

20 of the unit cell, such as in the column amplifier. For example, microbolometer 24 may be solely placed within the unit cell (along with associated selection circuitry, such as a row select transistor that is not shown).

Fig. 12 shows a circuit 60 providing temperature

25 compensation in accordance with another embodiment of the present invention. Circuit 60 is similar to circuit 44 of Fig. 7b, but includes a reference path 62. Reference path 62 includes thermally shorted microbolometers 66 and 74, variable resistor 68, a transistor 70, an amplifier 72, and a DAC 64.

30 DAC 64 provides a reference voltage to amplifier 72, which is used to appropriately bias transistor 70. DAC 64 and

- 15 -

resistor 68 are adjusted to provide a reference voltage for amplifier 28. Amplifiers 32 and 72 may have their reference voltage provided by a DAC or the reference voltage may be provided to amplifier 32 and/or 72 by a set reference voltage

5   level (e.g., ground). Furthermore, microbolometer 66 and/or microbolometer 74 may be replaced by a resistor, which would provide the necessary temperature dependent reference behavior.

Reference path 62 will be affected by changes in substrate temperature in a similar fashion as the remaining portions of

10   circuit 60. Consequently, the reference voltage to amplifier 28 will vary in temperature and, therefore, reference path 62 provides additional temperature compensation. Additionally, power supply noise from supply voltages 22 and 40 are reduced by the common mode input to amplifier 28.

15   Fig. 13 shows an exemplary circuit 80 for resistor 26 in accordance with an embodiment of the present invention. Circuit 80 includes a number of resistors R1 through Rn, where n is a number greater than one. By the appropriate selection of switches 82, which are separately referenced as 82(1) through

20   82(k), where k is a number greater than one, the desired resistance between nodes 84 and 86 can be set. Switches 82 may represent transistors, which could then be switched or controlled by a digital or analog signal. Therefore, circuit 80 provides a variable resistor whose value may be digitally

25   selectable.

Fig. 14 shows an exemplary enclosure 90 for a microbolometer FPA in accordance with an embodiment of the present invention. Enclosure 90 includes an optical element 92, such as a window or lens, through which incident infrared

30   radiation 1 travels to reach a microbolometer array 98 mounted on a substrate 96 that is physically and thermally secured and

attached to a surface 94 of enclosure 90. Optical element 92

may be made, for example, of silicon, germanium, or crystals

(e.g., irtran) and enclosure 90 may be made, for example, of

ceramic, iron-nickel alloy (e.g., Kovar), or metal or metal

5   alloys (e.g., steel). Enclosure 90 contains the microbolometer

FPA circuitry and provides appropriate electrical pins, bond

pads, or connections to couple to associated electronics, such

as to infrared camera electronics.

In a conventional microbolometer FPA packed assembly with a

10   thermo-electric cooler, there may be a dynamic range degradation

due to unwanted infrared radiation transmitted from the

enclosure of the microbolometer FPA if the enclosure were to

have a change in temperature independently from the sensor

(e.g., FPA). However, by implementing techniques discussed

15   herein, infrared radiation, such as from enclosure 90 is

factored into the calibration process and accounted for, which

reduces the associated dynamic range degradation.

Fig. 15 is a top-level flowchart 100 of a calibration

process in accordance with an embodiment of the present

20   invention. Flowchart 100 includes steps 102 through 110 for

calibrating a microbolometer FPA. Step 104 is a required step

and steps 102 and 106 through 110 may be optional steps,

depending upon the microbolometer FPA behavior or performance,

the desired application, and required performance. Figs. 16

25   through 19 provide exemplary detailed flowcharts pertaining to

steps 102 through 110.

The external resistance is calibrated in step 102. The

term "external resistance" refers, for example, to the

resistance of a resistor such as resistor 38 of Fig. 7a, which

30   is typically placed outside of the unit cell and is not part of

the variable (or trim) resistance (e.g., resistor 26 of

Fig. 7a). The external resistance or the value of the external

resistor may be digitally selectable and/or may be a global

resistor and may be on or off-chip (i.e., on or off the FPA or

the ROIC). Therefore, one external variable resistor or a few

5   external variable resistors may be sufficient for a large

microbolometer FPA. For example, as each microbolometer in the

array is sampled, the global external resistor is set to its

calibrated value, determined during the calibration process,

corresponding to that particular microbolometer, column, group,

10   or array of microbolometers. As discussed above, depending upon

the behavior of the microbolometers in the FPA, an external

resistor may not be required.

The variable resistance and offset is calibrated for each

microbolometer in step 104. The variable resistance or trim

15   resistance refers, for example, to the resistance of a resistor

(a trim resistor) such as resistor 26 in Fig. 7a. For example,

step 104 determines the amount of resistance to be placed in

series with each microbolometer in the FPA. Step 104 also

determines the amount of offset to be applied for each

20   microbolometer in the FPA. As an example, the determined offset

for each microbolometer may be set by using DAC 34 to control

the gate bias of transistor 30 via amplifier 32 in Fig. 7a.

Step 106 provides fine offset correction calibration for

each microbolometer circuit output over the desired substrate

25   temperature range. Various techniques may be employed to

provide a fine correction to each microbolometer circuit output

after step 104 and possibly step 102 are performed, because

these steps then provide a correctable microbolometer circuit

output over a wide range of substrate temperature. The

30   techniques may include various mathematical best-fit or offset

correction algorithms or look-up table methods to determine the

fine offset correction factor for a given temperature. For
example, Lagrange terms enable a polynomial offset correction to
be generated in real-time for each microbolometer that
compensates for variations in microbolometer circuit output over
5   FPA substrate temperature.

Step 108 provides gain calibration for each microbolometer.
The gain terms normalize the response of each microbolometer to
incident infrared radiation. This step may simply determine the
gain term independent of FPA substrate temperature or, in a more
10   general fashion, determine the gain term as a function of FPA
substrate temperature. Similar mathematical best-fit,
correction algorithms, or look-up table methods can be provided
for these terms. Step 110 provides an additional fine offset,
if required, for each microbolometer. The offset also may be a
15   function of FPA substrate temperature.

Fig. 16 is a detailed flowchart 120 for step 102 of
flowchart 100 in Fig. 15. Flowchart 120 provides exemplary
calibrations steps for calibrating the external resistor. Step
122 sets the trim resistor for each microbolometer to a target
20   value, such as the mean value of the trim resistor. The FPA
temperature is then set to a value (i.e., T1) within the desired
calibration or operation temperature range (step 124). For
example, T1 may represent the value of the minimum operating
temperature range. The external resistor is then set to one of
25   its "n" possible values (step 126) and the offset is calibrated
for each microbolometer (step 128), where the offset may be
calibrated using the procedure described below. The offset
value and microbolometer circuit output value, obtained after
application of the offset value, is stored (step 130) and steps
30   126 through step 128 are repeated for each of the n possible
external resistor values (step 132). The result is n pairs of

- 19 -

external resistor and offset values along with each
corresponding microbolometer circuit output value.

5   The FPA temperature is then changed to another value (e.g.,
T2) within the desired calibration range (step 134). The stored
external resistor and offset values are applied, for each value
of n, and the microbolometer circuit output value is recorded
(step 136). For each value of n, step 138 calculates the
difference between the microbolometer circuit output from step
136 (i.e., at T1) and the microbolometer circuit output from
10   step 132 (i.e., at T2) and then calculates the average
difference across the full array of microbolometers. Step 140
selects the external resistor value corresponding to the
smallest average difference obtained from step 138, with this
resistor value being the calibrated value of the external
15   resistor for the entire microbolometer FPA.

Fig. 17 is a detailed flowchart 150 for the trim resistance
calibration in step 104 of flowchart 100 in Fig. 15. Flowchart
150 provides exemplary calibration steps for calibrating the
trim resistor. Step 152 sets the FPA substrate temperature to
20   one extreme of the desired operating or calibration temperature
range (e.g., T1). The trim resistor is set to one of "m"
possible values (step 154), such as the minimum value, and then
the offset is calibrated (step 156) using a procedure, such as
the one described below. The offset value and the resulting
25   microbolometer circuit output value, after application of the
offset value, are recorded for the given trim resistor value
(step 158). Step 160 repeats steps 154 through 158 for each of
the m possible trim resistor values, which results in m pairs of
trim resistor/offset values and corresponding microbolometer
30   circuit output values.

Fig. 20 shows a graph and accompanying table illustrating a
calibration operation in accordance with an embodiment of the
present invention. Specifically, Fig. 20 provides an exemplary
illustration of the trim resistor calibration through step 160
5   of flowchart 150 for a single microbolometer and three possible
trim resistor values (i.e., m equals three). As can be seen in
the chart of Fig. 20, the microbolometer circuit output (or
pixel output) is plotted for a given FPA substrate temperature
(T1). The accompanying table provides a tabulation of trim
10   resistor value (RDAC value), offset value (ODAC value), and
pixel output value at temperature T1 for the three trim resistor
values. The labels "RDAC value" and "ODAC value" refer to the
resistor and offset values being digitally selectable or
controlled, as discussed above and illustrated in the figures.
15   The pixel output value is listed as a percentage of the
microbolometer circuit output dynamic range or desired output
range.

Returning back to Fig. 17, the FPA substrate temperature is
then changed to a value (T2) at the opposite extreme as the
20   prior value (T1) of the desired calibration or operating
temperature range (step 162). For each value of m, the
corresponding trim resistor value and offset value obtained in
steps 154 through 160 are applied and the microbolometer circuit
output value is recorded (step 164). Fig. 21 shows a graph and
25   accompanying table, illustrating step 164, in accordance with an
embodiment of the present invention. Fig. 21 is similar to Fig.
20, but now includes the three exemplary microbolometer circuit
output values obtained at temperature T2.

For each value of m (Fig. 17 - step 166), the difference is
30   calculated between the microbolometer circuit output from step
164 (i.e., at temperature T2) and the microbolometer circuit

- 21 -

output obtained from step 158 (i.e., at temperature T1). Step
168 selects the trim resistor value and associated offset value
that corresponds to the minimum difference from the results of
step 166. These values are the calibrated values for the trim

5   resistor and offset. Note that, if desired, the offset can be
re-calibrated at a different FPA temperature value or with a
different target value. This would provide a wider temperature
operating range and more well-behaved performance.

Fig. 22 shows a graph and accompanying table illustrating

10 steps 166 and 168 in accordance with an embodiment of the
present invention. Fig. 22 is similar to Fig. 21, but now
includes the difference calculation of values between the two
temperature settings and the selection of the trim
resistor/offset that generates the minimum difference.

15 For step 104 of flowchart 100 in Fig. 15, the offset value
is determined for each microbolometer in the FPA. The offset
value, for example, can be determined for each microbolometer by
using a binary search to find the offset value that adjusts the
microbolometer circuit output value closest to a desired value

20 (i.e., microbolometer circuit output target value). The
temperature of the FPA substrate and other parameters, such as
the flux incident on the FPA, should generally not vary
substantially while the offset calibration is in process.

Fig. 18 is a detailed flowchart 180 for step 106 of

25 flowchart 100 in Fig. 15. Flowchart 180 provides exemplary
calibrations steps for calibrating the fine offset correction
(e.g., Lagrange) terms for a microbolometer in the FPA array.
However, the exemplary procedure could be employed in the more
general case to calibrate many pixels simultaneously. Step 182

30 sets the FPA temperature to a value within the desired
calibration or operating range and records the measured

- 22 -

temperature value (having temperature units, such as Kelvin or
Celsius, or units of volts that correspond to a given
temperature). For this temperature, the microbolometer circuit
output is recorded after the application of the calibrated trim

5   resistor and offset values (step 184).

The FPA temperature is then changed, at step 186, to
another value within the desired temperature range and steps 182
and 184 are repeated. Step 188 repeats step 186 a minimum of
K+1 times, where K represents the desired order of the

10   polynomial correction. For example, a minimum of four terms is
stored if the third order polynomial correction is desired. The
polynomial correction results generally improve if two of the
K+1 points are at the opposite extremes of the desired
calibration range.

15   The gain of each microbolometer can be calibrated using a
two-point calibration process (e.g., at two different values of
incident flux) at any arbitrary FPA temperature. Alternatively,
the gain of each microbolometer can be calibrated as a function
of FPA temperature, such as in the calibration process described

20   below. Both procedures are similar to the fine offset (e.g.,
Lagrange) correction described above in reference to Fig. 18,
but the two procedures (i.e., gain and fine offset) differ from
each other in that instead of storing each microbolometer
circuit output at a single value of incident flux, each

25   microbolometer circuit output is stored for two values of
incident flux.

Fig. 19 is a detailed flowchart 200 for step 108 of
flowchart 100 in Fig. 15. Flowchart 200 provides exemplary
calibration steps for calibrating the gain of each

30   microbolometer. Step 202 sets the FPA temperature to a value
within the desired calibration or operating range and the

- 23 -

temperature value is recorded (in units of temperature, such as Kelvin or Celsius, or in units of voltage that correspond to a given temperature). Step 204 records the microbolometer circuit output difference for two flux levels or responsivity for that

5   temperature for each microbolometer. Step 206 changes the FPA temperature to another value within the calibration or operating range and the temperature value and each microbolometer circuit output is recorded. Step 206 is repeated (in step 208) a minimum of K+1 times, where k represents the desired order of

10   the polynomial fit of the gain terms.

Fig. 23 illustrates a compensation process 220 in accordance with an embodiment of the present invention. Compensation process 220 illustrates generally the overall compensation process for providing an optimal output from each

15   microbolometer in the FPA over the desired FPA temperature range. The microbolometer FPA is represented symbolically by an FPA 222. As shown, each microbolometer in the array receives a trim resistor ($Rtrim_i$, where i ranges from $1 \leq i \leq$ maximum number of microbolometers in the array) and an offset calibration

20   ($Offset_i$) adjustment. The trim resistor calibration and the offset calibration adjust each microbolometer circuit output over the calibrated temperature range from, for example, what is shown in Figs. 3 or 4 to what is shown in Fig. 8. An external resistor (Rext) calibration is also optionally performed as

25   described above, depending upon microbolometer FPA behavior. There may be an external resistor digitally selectable for each microbolometer or there may be one global external resistor that is calibrated for the entire microbolometer FPA.

The microbolometer circuit outputs from FPA 222 are

30   combined in block 224 with the calibrated temperature-dependent fine (e.g., Lagrange) offset 230. The fine offset may be

determined in any of a number of methods or techniques, as
discussed herein. Fig. 23 refers to the fine offset as Lagrange
offset 230, which is one exemplary method, but the fine offset
is not intended to be limited solely to this exemplary method.
5   Lagrange offset 230 provides the calibrated polynomial
correction values for each microbolometer circuit output, which
can be summed with each microbolometer circuit output from FPA
222. As shown in Figs. 8 and 10, the microbolometer circuit
outputs over the calibrated temperature range tend to produce a
10   curved or bowed output curve, after application of the trim
resistor, offset, and possibly external resistor calibrated
values. The application of Lagrange offset 230 refines the
microbolometer circuit output behavior and provides a more
uniform output (i.e., reduces the curve or bow in microbolometer
15   circuit output over temperature). Lagrange offset 230 receives
as inputs the measured substrate temperature and the Lagrange
terms (Lagrange $Term_i$), which are used to generate the Lagrange
offset terms uniquely for each microbolometer in the array.

A block 226 receives the microbolometer circuit outputs,
20   after application of the Lagrange offsets, and multiplies the
microbolometer circuit outputs by a corresponding calibrated
temperature dependent gain 232. The gain adjusts each
microbolometer circuit output to provide a more uniform response
to incident flux. As shown, the gain is temperature dependent
25   and receives as inputs the measured substrate temperature and
the gain terms (Gain $Term_i$), which are used to generate the
temperature dependent gain uniquely for each microbolometer in
the array.

A block 228 receives the microbolometer circuit outputs,
30   after application of the gain adjustment, and sums the
microbolometer circuit outputs with additional offset terms

(Offset$_i$), with the offset for block 228 typically differing from the offset input to FPA 222. For example, the offset term is updated periodically during camera operation using a shutter, a chopper, or a scene-based algorithm.

5   It should be appreciated that the implementation of the trim resistor within each microbolometer circuit provides the correctable microbolometer FPA performance over a wide temperature range. The correctable microbolometer FPA performance over the calibrated temperature range then permits

10   the application of Lagrange offset, gain, and offset calibration over the wide calibrated temperature range. It should also be appreciated that the principles of this invention may be implemented or applied to a wide variety of circuit devices and materials. Accordingly, the embodiments described herein are

15   only exemplary of the principles of the invention and are not intended to limit the invention to the specific embodiments disclosed.

       Fig. 24 shows a circuit 240 for providing temperature compensation in accordance with another embodiment of the

20   present invention. Circuit 240 is similar to circuit 44 of Fig. 7b, but illustrates that the voltage reference for amplifier 28 can be provided by a DAC 242. DAC 242 can be controlled to provide a varying voltage reference level, for example based on the measured substrate temperature.

25   Amplifier 32 may have its positive input terminal tied to a ground voltage level (as shown in Fig. 24) or set by DAC 34 (as shown in Fig. 7b).

       Fig. 25 shows a circuit 250 for providing temperature compensation in accordance with another embodiment of the

30   present invention. Circuit 250 includes supply voltages 22 and 40, microbolometers 24 and 36, resistors 26 and 38, transistors

30 and 252, DACs 254 and 256, an amplifier 258, an impedance
element (e.g., a switched capacitor network) 260, and output
voltage (Vout) 46.

Resistors 26 and 38, microbolometers 24 and 36, and supply
5   voltages 22 and 40 operate in a similar manner as discussed
above in reference to Fig. 7a and therefore the description will
not be repeated. DACs 254 and 256 are coupled to the gate
terminals of transistors 252 and 30, respectively, to control
the bias applied to microbolometers 24 and 36, respectively.
10   Specifically, DAC 254 adjusts the offset by controlling the bias
applied to microbolometer 24 in combination with resistor 26 via
transistor 252. DAC 256 adjusts the offset by controlling the
bias applied to microbolometer 36 in series with resistor 38 via
transistor 30.

15   Amplifier 258 and impedance element 260 form a
transimpedance amplifier, which translates the current level
flowing into the transimpedance amplifier into a voltage level
at output voltage (Vout) 46. Consequently, DACs 254 and 256
determine the amount of current flowing through respective
20   microbolometers 24 and 36 and also into the transimpedance
amplifier and, thus, set the offset and reference level of
output voltage (Vout) 46. DACs 254 and 256 can be calibrated,
as discussed above, for a single temperature or over a desired
operating temperature range for each microbolometer in the FPA
25   array.

Fig. 26 shows a circuit 270 for providing temperature
compensation in accordance with another embodiment of the
present invention. Circuit 270 is similar to circuit 250 of
Fig. 25, but a current source 272 is provided and resistor 26 is
30   eliminated. The amount of current flowing through
microbolometer 24 to produce a microbolometer bias current

(IbiasB) is reduced by the contribution of current by current
source 272.   Therefore, the voltage across microbolometer 24 is
reduced and the change in the contribution of current (Ibolo)
through microbolometer 24 to the microbolometer bias current

5   (IbiasB) as a function of temperature is fractionally reduced.
Thus, current source 272 has effectively lowered the TCR of
microbolometer 24.

Fig. 27 shows a microbolometer readout integrated circuit
with bias-correction circuitry and interface system electronics

10   in accordance with an embodiment of the present invention.   Fig.
27 includes a readout integrated circuit (ROIC) 282 that
includes the microbolometer FPA, control circuitry, timing
circuitry, bias circuitry, row and column addressing circuitry,
column amplifiers, and associated electronics to provide output

15   signals that are digitized by an analog-to-digital (A/D)
converter 284.   The A/D converter 284 may be located on or off
ROIC (282).

The output signals from A/D converter 284 are adjusted by a
non-uniformity correction circuit (NUC) 285, which applies

20   temperature dependent compensation (e.g., Lagrange Offset,
Temperature Dependent Gain, and additional Offset) as discussed
above, such as in reference to Fig. 23.   After processing by NUC
285, the output signals are stored in a frame memory 286.   The
data in frame memory 286 is then available to image display

25   electronics 288 and a data processor 292, which also has a data
processor memory 290.   A timing generator 294 provides system
timing.

Data processor 292 generates bias-correction data words,
which are loaded into a correction coefficient memory 298.   A

30   data register load circuitry 296 provides the interface to load
the correction data into readout integrated circuit 282.   In

this fashion the variable resistors, digital-to-analog
converters, and other variable circuitry, which control voltage
levels, biasing, circuit element values, etc., are controlled by
data processor 292 so that the output signals from readout
5   integrated circuit are uniform over a wide temperature range.

Embodiments described above illustrate but do not limit the
invention. It should also be understood that numerous
modifications and variations are possible in accordance with the
principles of the present invention. Accordingly, the scope of
10   the invention is defined only by the following claims.